29th International Cosmic Ray Conference Pune (2005) **5**, 67–70

High energy neutrinos from microquasars

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We calculate the neutrino event rates from the jet in very compact, massive binary containing stellar mass black hole or a neutron star. A part of the jet kinetic energy, typically $\sim 10\%$, can be transfered to relativistic nuclei. These nuclei lose nucleons as a result of photo-disintegration process in collisions with thermal photons from the accretion disk and the massive star. Due to the head on photon-nucleus collisions most of neutrons released from nuclei move towards the surface of the accretion disk and/or the massive star producing neutrinos in collisions with the matter. Such model predicts up to several neutrino events per km^3 per yr from Cyg X-3, provided that nuclei are accelerated to the Lorentz factors above 10^6 with a power law spectrum with an index close to 2.

1. Introduction

High energy processes play an important role in the massive binaries since some of them emit high energy X-rays and γ-rays. However, the content of these jets, hadronic, leptonic or mixed, remains a puzzle. We consider a model for the neutrino production in microquasars in which nuclei are accelerated in the jet launched from the inner part of the accretion disk. The disk is formated by the matter accreting onto the black hole from the massive companion. We show that in very compact binaries of the Cyg X-3 type, nuclei accelerated in the jet can lose efficiently neutrons in collisions with the stellar and accretion disk radiation. Most of these neutrons propagate towards the disk and the massive star producing neutrinos in collisions with the matter.

2. A compact object close to a massive star

Let's consider a solar mass black hole or a slowly rotating neutron star on a close orbit around a Wolf-Rayet (WR) star. The matter accreting from the massive star forms an accretion disk which launches a jet from its inner part as observed in microquasars. As an example, we consider a specific case of the Cyg X-3 binary system which basic parameters are the following: the Wolf-Rayet star with the surface temperature $T_{\rm WR} = 1.36 \times 10^5$ K and radius $R_{\rm WR} = 1.6R_\odot$, the separation of the components $D = (3.6 \pm 1.2)R_\odot = 2.25R_{\rm WR}$. Persistent X-ray emission of the accretion disk in Cyg X-3 is $L_{\rm d} \approx 10^{38}$ erg s^{-1} [1]. For this disk luminosity, and an assumed inner radius of the disk $R_{\rm d} = 10^7$ cm, the inner disk temperature is $T_{\rm d} \sim 10^7$ K. According to the the disk-jet symbiosis model proposed by Falcke et al. [2], the jet power, $L_{\rm j}$, is comparable to the observed disk luminosity, $L_{\rm d}$. Therefore, in farther considerations we assume $L_{\rm j} = 0.5L_{\rm d} = 5 \times 10^{37}$ erg s^{-1}. Note however, that in the outburst stages, which are relatively frequent in Cyg X-3, the X-ray luminosity can be several times larger. The jet in Cyg X-3 propagates with the velocity in the range (0.3-0.8)c (c is the velocity of light), estimated from the expansion rate of specific components [3] and the ratio of the jet to counter-jet flux [4]. We apply the average value, $v_{\rm j} = 0.5c$ [5].

The WR stars are at the late stage of evolution of the supermassive stars which have already lost their hydrogen envelopes. Their winds are mainly composed from the CNO group of nuclei. We assume that these nuclei can be accelerated in some regions of the jet to relativistic energies. However, location of the acceleration place, the dissipation region, in the jet is unknown and depends on the details of the acceleration model. Therefore, we consider three different possible regions:

(I) Nuclei accelerated to sufficient energies very close to the base of the jet are immediately disintegrated in collisions with X-ray photons from the inner accretion disk. Nucleons from their disintegration may interact with the X-ray photons producing neutrinos through decay of pions, provided that they have Lorentz factors above the threshold for pion production, $\gamma_\pi^{\rm min} \approx m_\pi/6k_{\rm B}T_{\rm d} \approx 10^5$, where m_π is the pion mass and $k_{\rm B}$ is the Boltzmann constant. Such scenario is realized if the optical depth for pion production by nucleons in collisions with the disk photons is above unity. The extent of the region (I) can be estimated by comparing the characteristic escape time of nucleons with the jet plasma, $\tau_{\rm esc} = xR_{\rm d}/v_{\rm j}$, where x is the distance along the jet in units of the inner disk radius $R_{\rm d}$, with the interaction time of nucleons $\tau_{N\varepsilon\to\pi} = (n_{\rm d}\sigma_{N\varepsilon}c)^{-1}$, where $\sigma_{N\varepsilon} = (1-4)\times 10^{-28}$ cm^2 is the cross section for proton-photon pion production in the region of the plateau and the peak, respectively. The photon density from the inner disk is approximated by $n_{\rm d} \approx 4\sigma_{\rm SB}T_{\rm d}^4/(3ck_{\rm B}T_{\rm d}x^2) \approx 2\times 10^{16}T_5^3/x^2$ ph. cm^{-3} where $T_{\rm d} = 10^5T_5$ is the disk temperature at its inner radius, $\sigma_{\rm SB}$ is the Stefan-Boltzmann constant. Region (I) extends up to $x_{{\rm N}\varepsilon\to\pi} \approx (40-170)$, i.e. at $\sim (4-17)\times 10^8$ cm from the base of the jet. We do not consider here the region (I) since it has been discussed recently [6].

(II) Nucleons from disintegration of nuclei are not able to produce efficiently pions in collisions with the disk radiation but they are able to fragment significantly on separate nucleons. Due to the head on collisions of the nuclei with photons, neutrons move towards the inner disk producing neutrinos in collisions with the matter. Such general picture (with the difference of injection of neutrons by protons) has been proposed for the accretion disks in active galactic nuclei [7]. The region (II) extends along the jet to the distance, $x_{\rm d/s}$, at which density of photons from the disk becomes comparable to that from the WR star. By comparing these photon densities, we estimate $x_{\rm d/s} \approx 10^3$. The photon density from the massive star at the distance equal to the separation of the components is $n_{\rm WR} \approx 4\sigma_{\rm SB}T_{\rm WR}^4/(3ck_{\rm B}T_{\rm WR})(R_{\rm WR}/D)^2$.

(III) In this region radiation from the WR star dominates. As we show later it is at least an order of magnitude larger than the inner regions dominated by the radiation of the accretion disk. Neutrons extracted from nuclei in the region (III) move mainly towards the surface of the WR star due to the head on collisions of nuclei with the stellar photons.

3. Relativistic nuclei in the jet

In order to estimate the maximum energies of nuclei accelerated in the jet, let us assume that the magnetic field energy density in the inner part of the accretion disk (at the base of the jet) is in the equipartition with the energy density of radiation, i.e. $U_{\rm B} \approx U_{\rm d}$. For the disk temperature at the inner radius, $T_{\rm d} = 10^7$ K, the magnetic field can be as large as $B_{\rm d} \approx 3\times 10^7$ G. The magnetic field drops along the jet according to $B(x) = B_{\rm d}/(1+\alpha x) \approx B_{\rm d}/x$ (for $x \gg 1/\alpha$), where $\alpha = 0.1$ rad is the jet opening angle. The acceleration rate of nuclei can be expressed by $d\gamma_{\rm A}/dt = \xi ZeBc/Am_{\rm p}$, where ξ is the efficiency of acceleration mechanism, Am_p, and Ze are the mass and the charge of the nuclei, and $Z/A = 0.5$. Nuclei are accelerated in a characteristic distance, $L_{\rm acc} \approx \alpha xR_{\rm d}$, to the maximum Lorentz factor, $\gamma_{\rm A}^{\rm max} \approx \alpha xR_{\rm d}(d\gamma_{\rm A}/dt)/c = \xi eB_{\rm d}R_{\rm d} \approx 10^8\xi$. Heavy relativistic nuclei can lose efficiently nucleons due to the photo-disintegration process in collisions with thermal photons from the accretion disk or the massive star if photon energies in the reference frame of the nuclei are above ~ 10 MeV, i.e. $E_\gamma = 6k_BT\gamma_A = 5\times 10^{-5}T_5\gamma_{\rm A}$ MeV > 10 MeV. This condition gives the lower limit on the Lorentz factor of accelerated nuclei above which their photo-disintegration becomes important, $\gamma_A^{min} \approx 2\times 10^5/T_5$. The most efficient disintegrations occur when the photon energies correspond to the maximum in the photo-disintegration cross-section of nuclei, which is at ~ 20 MeV (with the half width of ~ 10 MeV) [8], for nuclei with the mass numbers between helium and oxygen.

Let's estimate the efficiency of the photo-disintegration process of nuclei in the region II and III. The mean free path for dissociation of a single nucleon from the nuclei is $\lambda_{A\gamma} = (n\sigma_{A\gamma})^{-1}$, where n is the density of thermal photons coming from the accretion disk, or the WR star, $n_{\rm WR}(r) \approx 4\sigma_{\rm SB}T_{\rm WR}^3/3ck_{\rm B}r^2$, where $r = R/R_{\rm WR}$, and R is the distance from the WR star. The photo-disintegration cross section at the peak of the giant resonance and the plateau region after the resonance are: $\sigma_{\rm A\gamma}^{\rm r} \approx 1.45 \times 10^{-27}A$ cm^2 (valid for $\gamma_{\rm A} \leq 3 \times 10^6$), and $\sigma_{\rm A\gamma}^{\rm p} \approx 1.25 \times 10^{-28}A$ cm^2 ($\gamma_{\rm A} > 3 \times 10^6$) [9]. The characteristic photo-disintegration time scales of nuclei with the mass number A in the radiation field of the accretion disk ($T_{\rm d} = 10^7$ K) and the WR star ($T_{\rm WR} = 1.36 \times 10^5$ K), $\tau_{\rm A\gamma} = \lambda_{\rm A\gamma}/c$, are $\tau_{\rm A\gamma}^{\rm d} \approx (2.5 - 20) \times 10^{-6}x^2/A$ s and $\tau_{\rm A\gamma}^{\rm WR} \sim (0.5 - 4)r^2/A$ s, respectively. On the other site, the convection escape time of nuclei along the jet is of the order of $\tau_c \approx \sqrt{R^2 - D^2}/v_{\rm j}$, equal to $\sim 8r$ s (if $R \gg D$). By comparing $\tau_{\gamma A}^{\rm WR}$ and τ_c, we get the upper limit for the distance from the Wolf-Rayet star, $r_{\rm max} \approx (2 - 15)A$, below which the photo-disintegration process of nuclei is important. This is the upper bound on the region (III). Nuclei accelerated in the region (III) lose neutrons which fall onto the Wolf-Rayet star up at angles β (measured from the plane of the binary system) which fulfill the condition: $\cos\beta = D/(r_{\rm max}R_{\rm WR}) \approx (0.15 - 1)/A$.

In order to determine the conditions for acceleration of nuclei let us compare the acceleration time scale, $\tau_{\rm acc} = \gamma_{\rm A}/(d\gamma_{\rm A}/dt) \approx x\gamma_{\rm A}/(3 \times 10^{12}\xi)$ s, with the photo-disintegration time scale, $\tau_{\rm A\gamma}$. The maximum Lorentz factor to which nuclei can be accelerated before significant disintegration are then: $\gamma_{dis}^{\rm II} \approx 7.5 \times 10^6\xi x/A$ and $\gamma_{dis}^{\rm III} = 7.5 \times 10^{12}\xi/(Ax)$, for the region (II) and (III) respectively (applying $r = 2.25$, $\alpha = 0.1$, and $A = 14$). The comparison of these Lorentz factors with the minimum Lorentz factor of nuclei for the efficient photo-disintegration process (see Eq. 4) allows us to estimate the required value of the acceleration efficiency in the regions II and III, $\xi_{\rm th}^{\rm II} \approx 10^{-5}$ (for $x = 300$) and $\xi_{\rm th}^{\rm III} \approx 3 \times 10^{-3}$ (for $x = 10^4$), above which nuclei at first obtain the power law spectrum and then lose separate neutrons. Neutrons separated from nuclei also have a power law spectrum with the spectral index of the parent nuclei. If $\xi < \xi_{\rm th}$, neutrons are injected by nuclei with the Lorentz factors close to $\gamma_{\rm A}^{\rm min}$, i.e. they are almost mono-energetic. Therefore, we consider the injection of neutrons by nuclei with the mono-energetic and the power law spectra.

4. Production of neutrinos

Most of neutrons extracted from nuclei in the region (II) move towards the inner part of the accretion disk and from the region (III) towards the massive star producing neutrinos and γ-rays in hadronic interactions with the matter. γ-rays, from the decay of neutral pions, are absorbed by very high column density of matter (accept a narrow region around the stellar limb) but neutrinos can pass through the main part of the interior of the star without absorption. For the parameters of the Wolf-Rayet stars the optical depth is larger than unity only for neutrinos moving close to the center of the star, i.e. with the impact parameter less than $\sim 0.2R_{\rm WR}$ which corresponds only to a few percent of the full stellar disk [10]. Therefore, the fraction of neutrinos absorbed inside the star is relatively low and can be neglected. We calculate the muon neutrino (and anti-neutrino) spectra produced by neutrons with the mono-energetic and the power law spectra. The multiple interactions of neutrons with the matter have been taken into account up to their cooling to 100 GeV. We apply the scaling break model for hadronic interactions [11]. The neutrino spectra are calculated for the mono-energetic nuclei accelerated in the region (II) to the Lorentz factors 2×10^3 and for the power law spectrum with the spectral indexes equal to 2 and 2.5 and the cut-offs at Lorentz factors 10^7 and 10^6. We apply the distance to the Cyg X-3 binary system equal to 10 kpc and assume that $\chi = 10\%$ of the jet energy is transported to relativistic nuclei.

5. Conclusion

To estimate the neutrino event rate in a 1 km^3 neutrino detector from the Cyg X-3 type binary system we apply the likelihood of neutrino detection by a 1 km^3 detector [12]. We consider two limitting cases, i.e. the source close to the horizon (neutrinos not absorbed by the Earth), and the source at the nadir (neutrinos partially absorbed). The number of events per year per km^3 expected for the mono-energetic injection of nuclei in the region III is ~ 24 events, and for nuclei with the power law spectrum in the region II (and the region III): 16.5 (14) events for the spectral index $\alpha = 2$ and the cut-off at the Lorentz factor $\gamma_{\rm A}^{max} = 10^7$, and 11 (8.3) events for the cut-off at 10^6, and ~ 2 (~ 1) events for $\alpha = 2.5$ and $\gamma_{\rm A}^{max} = 10^7$. Since the neutrino spectra do not extend much above a few 10^5 GeV, the effects of absorption of neutrinos in the Earth are only of the order of $\sim 10\%$. Such event rates should be detected above the ANB by the IceCube detector if the spectrum of accelerated nuclei is flatter than 2.5. Note that predicted neutrino signals from the regions (II) and (III) should be emitted in completely different directions. Neutrinos from the accretion disk are collimated along the axis of the jet. In contrast, neutrinos from the WR star are emitted inside the broad solid angle around the plane of the binary system and should be modulated with the orbital period of the binary system reaching the maximum when the compact object is behind the Wolf-Rayet star. This should help to separate the neutrino signal from the ANB. Therefore, even smaller scale neutrino detectors, e.g. of the AMANDA II and Antares type, might be also able to detect such microquasars in compact massive binaries within our Galaxy or at least put strong constraints on the efficiency of hadron acceleration in their jets. The angular features of the neutrino emission, coupled with the information on the geometry of the binary system, should allow to distinguish between the two discussed regions for hadron acceleration giving information on the acceleration process and formation of jets.

Acknowledgments

This work is supported by the MNiI grant No. 1P03D 010 28 and the KBN grant PBZ KBN 054/P03/2001.

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